$^{40}Ar/^{39}Ar$ dating of detrital mica from the Upper Paleozoic sandstones in the Western Carpathians (Slovakia)

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Abstract: Dating of detrital white mica taken from the Carboniferous-Permian sediments of the Western Carpathians provided powerful results for determination of source areas. Two groups of samples were studied, first from the Carboniferous formations of the Northern Gemeric Unit and second from the Pennsylvanian-Permian sequence of the Hronic Unit. Both units are extremely important for the geodynamic reconstruction of the Western Carpathian Variscan Orogen, as the Northern Gemeric Late Paleozoic reflects the development of a Variscan collision suture and the sedimentary history of Hronicum formations allows reconstruction of the timing of rifting processes in the hinterland. Rift-related sediments of the Hronic Unit show a trend of increasingly older detrital mica in an upward direction. Three samples from the Nižná Boca Formation, belonging to Kasimovian–Gzhelian (Stephanian B-C), were investigated from the Hronic Unit. The stratigraphically lowest sample yielded an age of 309 ± 3 Ma. The samples from the middle and upper portion of the Nižná Boca Formation delivered successively older ages of 318 ± 2 Ma and 329 ± 2 Ma respectively. The time gap between the average cooling in the source region and the age of sedimentation in the basal part of the Nižná Boca Formation does not exceed 5 Myr, whereas at the top of the same formation this time difference reaches about 20 Myr. The trend to older ages in higher stratigraphic levels in this tectonic unit is further corroborated by a sample derived from the Permian Malužiná Formation, 2nd megacycle, which yielded a still older age of 342 ± 3 Ma. These cooling ages of the source area reflect development of the Hronicum terrestrial rift and heterogeneity of the source area, with gradual rifting and cooling of the lithosphere. Four samples from the Northern Gemeric Unit were also investigated. A multi-grain sample from the Mississippian Hrádok Formation yielded a 465 ± 2.5 Ma cooling age of the source area. This proves the existence of Ordovician crustal fragments in the Variscan collision suture. Newly-formed fine-grained muscovite gave a distinct staircase pattern from 87 Ma at the rim to 142 Ma in the core. It reflects composite Alpine overprint of these metasediments. Multi-grain analyses of detrital mica from the Moscovian (Westphalian) Rudňany Formation sandstone and from an orthogneiss pebble from the associated conglomerate yielded ages of 385 ± 3 Ma and 372 ± 2.5 Ma, which reflect a uniform Variscan source.

Key words: Western Carpathians, Upper Paleozoic sandstones, $^{40}Ar/^{39}Ar$ dating, source area, detrital mica.

Introduction

The present Alpine chain is built on continental crust consolidated at the end of the Variscan orogenic cycle. The pre-Mesozoic Western Carpathian basement registered all the main orogenic periods during its long evolution since the Precambrian, which led to stepwise converging of Gondwana-type pieces of crust (detached from Gondwana) and to their final continent–continent collision in the Variscan orogenic belt from the Late Devonian to the Carboniferous time. Due to development of syn- and post-orogenic Carboniferous and Permian sedimentary basins, relics of which are preserved in all units of the Inner Western Carpathians (Fig. 1), the detrital material derived from the newly formed orogenic belt was preserved.

The $^{40}Ar/^{39}Ar$ age of detrital mica grains in Upper Paleozoic sandstones provides direct evidence for the ages of source areas from which the sand detritus was derived. The interpretation of provenance has to consider the post-sedimentary evolution of the studied rocks, especially the Alpine low-grade metamorphic overprint in some tectonic units. Samples rich in detrital micas were collected from Carboniferous metasandstones and sandy metapelites from the Northern Gemeric Unit and Pennsylvanian and Permian sandstones from the Hronic Unit (Fig. 1). Both units are extremely important for the geodynamic reconstruction of the Western Carpathian Variscan Orogen, as the Northern Gemeric Late Paleozoic reflects the evolution of a Variscan collision suture. Additionally, the basal clastics of the Hronicum can yield information on the former basement of this unit and throw new light on the continental rifting process responsible for the formation of these deposits.

Geological setting

Like most other collision fold belts, the Western Carpathians have been traditionally divided into external and

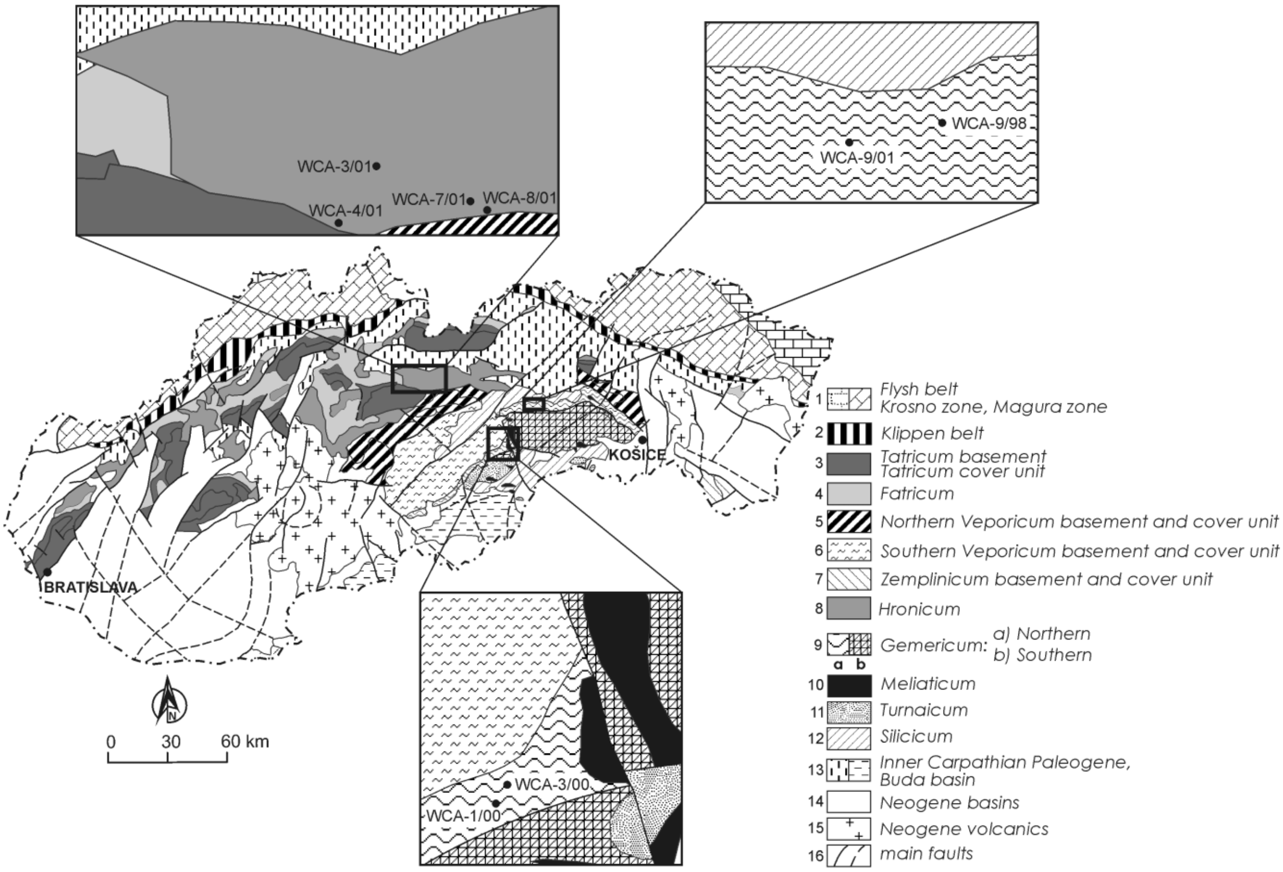

Fig. 1. Map showing the main tectonic units of the Slovak part of the Western Carpathians, studied area and localization of samples (modified after Biely et al. 1996).

internal structural zones, which are divided by the Pieniny Klippen Belt (for summary see Biely et al. 1996a,b; Plašienka 1995, 2003). The main differences between these structural zones are the age of the main Alpine events and the intensity of their deformational and metamorphic effects. These are: (1) **external zone**, the Late Cretaceous/Early Paleocene to Oligocene/Early Miocene subduction/accretion and collision events; (2) **internal zone**, the Late Jurassic HP/LT subduction event and Early/middle Cretaceous collision, associated with nappe stacking.

The internal part of the Western Carpathian orogenic system is divided into the pre-Gosau nappe system and overlying post-nappe Upper Cretaceous to Neogene sedimentary and volcanic formations. The pre-Gosau nappe system originated from sedimentary basins deformed during Kimmerian to Mediterranean phases. Each such unit consists of a crystalline basement and a characteristic Upper Paleozoic/Mesozoic envelope sequence, which either rests on its original basement (Tatricum, Northern and Southern Veporicum, Zemplinicum, Northern and Southern Gemericum) or was detached and displaced as a nappe onto a different basement (Hronicum, Meliaticum, Turnaicum and Silicicum). Continental Upper Paleozoic sediments, unconformably overlain by Lower Triassic quartzose clastic deposits and Middle Triassic shallow-water carbonate are characteristic for Tatricum, Veporicum, Zemplinicum and Hronicum. The Carpathian Keuper Formation is typical of the Late Triassic of the Tatricum and Northern Veporicum, contrasting with dolomites and limestones in the Hronicum.

The fragments of the Upper Paleozoic sedimentary basin fillings, as well as their substrate are preserved only within the internal Western Carpathians, as part of the principal Alpine crustal-scale units (Tatricum, Northern and Southern Veporicum, Zemplinicum, Northern and Southern Gemericum), and several cover nappe systems (Hronicum, Meliaticum, Turnaicum and Silicicum). As mentioned above, the investigation is focused on $^{40}Ar/^{39}Ar$ multigrain dating of detrital white mica from the Carboniferous rocks of the Northern Gemeric Unit and from the Pennsylvanian and Permian rocks of the Hronic Unit (Fig. 1).

The *Hronicum* is a rootless Alpine unit, partly divided into two subunits — Šturec and Choč Nappes (Andrusov et al. 1973). Both subunits contain Late Paleozoic volcano-sedimentary formations, variably preserved as a consequence of tectonic reduction during nappe thrusting. Remains of these sedimentary complexes are known in many mountain ranges in the Western Carpathians; the best preserved segments being situated on the northern slopes of the Nízke Tatry Mts. There are no remnants of the underlying pre-Kasimovian–Gzhelian (pre-Stephanian) basement. Tectonic slices of granitoid blastomylonites found in the basal part of the Šturec Nappe may be indicative of its composition (Andrusov 1936; Vozárová & Vozár 1979). The Nižná Boca Formation, Stephanian according to macroflora (Sitár & Vozár 1973) and microflora (Planderová 1979), is a generally clastic regressive sequence with distinct tendency of coarsening upward. Abundant massive and graded-bedded grey or dark-grey sandstones with minor mudstone intercalations, as well as layers rich in coalified plant detritus indicate a fluvial-lacustrine delta association. Syngenetic volcanism is represented by dacitic volcaniclastic detritus mixed with non-volcanic material, less frequently by thin dacite tuff layers and small lava flows. The Permian sedimentary rock complexes (the Malužiná Formation) are developed gradually from the underlying Stephanian. They comprise a thick succession of red-beds which developed in three regional megacycles arranged above each other. An integral part of this formation is the polyphase rift-related andesite-basalt volcanism with a continental tholeiitic magmatic trend (Vozár 1977, 1997; Dostal et al. 2003). The microflora proved the Early and Late Permian age of the Malužiná Formation (Planderová 1973; Planderová & Vozárová 1982). This assumption is supported by $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ dating of 263 ± 11 Ma copper sulphides from uranium-bearing layers of the upper part of the second megacycle (Legierski in Rojkovič et al. 1992).

The *Northern Gemeric Unit* comprises relics of Bashkirian-Visean flysch (the Hrádok and Črmeľ Formations in the Ochtiná Group; Vozárová 1996) and fragments of two Variscan terranes (the Klátov and Rakovec Terranes; Vozárová & Vozár 1996), which differ from each other in tectono-metamorphic development and probably also in protolith age. Their gradual amalgamation took place in the Mississippian. This can be concluded from the uppermost Visean-Serpukhovian shallow-water carbonate-clastic development (the Lubeník Formation; Vozárová 1996) which after stratigraphic hiatus in the Bashkirian (Namurian B–C), is unconformably overlapped by Moscovian marine post-orogenic sediments. This overstepping marine "molasse" also rests on Mississippian flysch (in the eastern part of the Northern Gemeric Zone) and therefore seals a late Variscan thrust belt. Detrital micas were also dated from the Mississippian metasandstones of the Hrádok Formation and from metasandstones of the Pennsylvanian Rudňany Formation.

The Hrádok Formation consists of a dark-grey and black clastic flysch sequence — metaparaconglomerates, metasandstones, metapelites, interlayered with metabasalts, metamicrodolerites and basic metavolcaniclastics. Very rare sedimentary rocks, found only in thin layers, are lydites and siliceous metapelites. Slabs of ultramafic rocks (oceanic crust fragments) represented by antigoritic serpentinites and tremolite-talc schists are integral part of this deep-water turbidite slope/rise sequence. A monotonous complex of dark-grey metapelites, overlying the relatively coarse-grained basal part of the Hrádok Formation, yielded microflora indicating the Late Tournaisian–Visean age (Planderová 1982; Bajaník & Planderová 1985).

Moscovian (Westphalian) formations (Dobšiná Group consisting of Rudňany, Zlatník and Hámor Formations; Vozárová 1996) are preserved within the Northern Gemeric Unit as tectonically reduced fragments. Basal conglomerates of the Rudňany Formation unconformably overlap the Klátov Terrane gneiss-amphibolite complex, metasediments and metabasalts of the Rakovec Terrane as well as the Mississippian flysch sequence of the Črmel Formation in the eastern part of Northern Gemeric Unit. Coarse-grained delta-fan sediments contain detritus derived from these underlying pre-Pennsylvanian rock complexes. Black shales and micaceous metasandstones are a normal member of the fining upward Rudňany Formation. The floral finds (Němejc 1947) confirm the Westphalian A–B age.

Sample description

Hronic Unit: Three samples (WCA-4/01; WCA-7/01; WCA-8/01) were selected for age determinations from the Nižná Boca Formation sandstones. The dominant components are quartz grains (from 44 to 55 %), lithic fragments (from 13 to 19 %), feldspars (from 11 to 14 %) and clastic mica (from 2 to 7 %), with variable contents of primary matrix (from 14 to 25 %). Fragments of dacitic volcanites and their volcaniclastics, as well as different types of phyllites and metaquarzites were recognized among the lithic clasts (ratio Lv/L = 0.77). Plagioclase prevails among the feldspar clasts (plagioclase/alkaline feldspar ratio is 0.6). The matrix is slightly recrystallized, with newly-formed illite, chlorite and calcite.

Clastic mica of the Malužiná Formation sandstone (WCA-3/01) was separated from the upper part of the 2nd megacycle. Compared with the Nižná Boca Formation sandstones this sediment is rich in feldspar. Generally, sandstones from the 2nd megacycle of the Malužiná Formation contain: 49–58 % quartz grains, 10–12 % alkali feldspars, 8–9 % plagioclase, 6–7 % clastic mica, 1–3 % volcanic clasts, 0.5–1 % other lithic clasts (mostly different type of phyllites) and 15–22 % matrix, rich in hematite pigment.

Generally, the grade of metamorphism did not exceed the diagenesis/anchizone boundary (according to pumpellyite + prehnite assemblages in diorite dykes: Vrána & Vozár 1969; illite crystallinity indices from pelites: Plašienka et al. 1989; Šucha 1989).

Northern Gemeric Unit: Two groups of detrital mica were analysed from the Rudňany Formation. The first of these was derived from a white orthogneiss pebble of the Rudňany Formation boulder conglomerates (WCA-9/01) and the second from the sandstones associated with the plant-bearing horizon in the upper part of the Rudňany Formation (WCA-9/98). Components of the Rudňany conglomerates are different gneiss types, amphibolites, metabasalts and their volcaniclastics and metasediments (more detail see Vozárová 1973; Vozárová & Vozár 1988).

The white gneiss pebble is represented by medium-grained, medium-banded orthogneiss showing structural features of foliated granitic-gneiss. The porphyroblasts of alkali feldspars ($Or_{95}Ab_5$) and plagioclases ($Ab_{88-74}An_{9-25}Or_{0.3-1.7}$) are associated with quartz occurring in the bands of mosaic type crystals, muscovite (content of TiO_2

is ranging from 0.23 to 1.22 wt. %; Na/Na+K=0.04–0.06; Fe/Mg=0.46–2.45) and strongly altered biotite (transformed into iron-rich chlorite). Zircon and garnet (Alm_{68-70} Pyr_{3-8} Grs_{2-20} Sps_{5-22}) are the principal accessory minerals.

The mineral composition of associated sandstones reflects the same source area as the Rudňany conglomerates, namely a newly formed Variscan mobile zone. The sandstones are rich in lithic fragments (51 %), with less quartz (36 %) and feldspars grains (13 %) and detrital mica (2 %) (average of 8 analyses). The primary matrix is recrystallized consisting of newly-formed chlorite+muscovite+quartz. The grade of Alpine metamorphism corresponds to the lower greenschist facies (IC=0.21–0.23 [Δ °2Θ], Ir=1.0–1.08; Vozárová & Šucha, unpublished). Coarse- to medium-grained metasandstones of the Mississippian Hrádok Formation are generally relatively rich in quartz (in most samples more than 80 %). Subordinate components are plagioclase, detrital mica and lithic fragments. Primary coarse-grained detrital mica was separated from sample WCA-1/00. The strong Alpine overprinting is documented by fine-grained metamorphic mica, which was separated from sample WCA-3/00.

Generally, the rocks of the Ochtiná Group were metamorphosed in LP greenschist facies (Sassi & Vozárová 1987; geothermal gradient approx. 40 °C/km, estimated T=350–370 °C at a low pressure). The illite crystallinity indices correspond to these estimates (in the range of 0.17–0.23 [Δ °2Θ]; Ir index=1; Vozárová & Šucha, unpublished). These assessments are supported by the assemblage Act+Chl+Alb+Ep in the associated metabasic rocks. A Variscan age of metamorphism is suggested by the presence of pebbles derived from the lithologically and stratigraphically corresponding rock complex (Črmeľ Formation) within the Westphalian conglomerates in the eastern part of Northern Gemericum. A distinct Alpine overprinting is assumed.

Analytical procedure

The geochronological investigations were performed in the Ar laboratory of the Institute for Geological Sciences, Vienna University in 2002. The analytical procedure is the same as described in Frimmel & Frank (1996).

Interpretation of the ages

General remarks: The carefully separated and cleaned samples of detrital muscovites were measured in the form of multigrain samples of a few mg, which means that the spectra represent an average age of several thousands of individual grains. One can assume that during the separation procedure mainly the rims of the grains have been removed and therefore the obtained age spectra mainly reflect information from the inner portions of the detrital grains. The disturbances in the low temperature steps do not exceed a few percent. Apart from the reason just mentioned, this is well in line with the absent or negligible thermal overprint of the samples and the well preserved state of the detrital micas.

In addition to the now available age spectra of multigrain samples, histograms of single grain ages are needed to understand the age variation among the detrital micas in a single sample. Such investigations are planned in a more detailed future study. However, we feel that the rather well defined plateau-type age patterns of the diagrams indicates that mixing of micas from source regions with largely different ages or thermal histories with discordant age patterns was limited or missing. Apart from one sample of the Hrádok Formation the results reflect a provenance from various domains of the evolving Variscan Orogen.

Samples from the Hronic tectonic unit: Three samples from the Nižná Boca Formation, belonging to Stephanian B-C, have been investigated from this unit. The stratigraphically lowest sample (WCA-8/01) yielded an age of 309±3 Ma (Fig. 2, Table 1). The samples (WCA-7/01; WCA-4/01) from the middle and upper portion of the Nižná Boca Formation delivered successively older ages of 318±2 Ma and 329±2 Ma respectively (Figs. 3, 4; Tables 2, 3).

The time gap between the average cooling in the source region and the age of sedimentation in the basal part of the Nižná Boca Formation does not exceed 5 Myr, whereas on top of the same formation this time difference reaches about 20 Myr. If we assume that the result from these

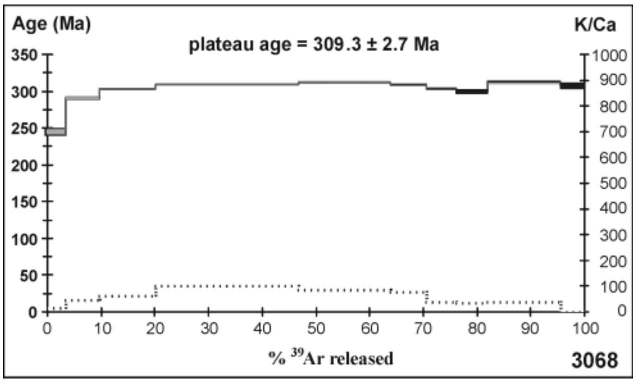

Fig. 2. $^{40}Ar/^{39}Ar$ apparent age diagram of detrital white mica from the basal part of the Nižná Boca Formation, sample WCA-8/01.

Table 1: Analytic data of detrital white mica from the basal part of the Nižná Boca Formation, sample WCA-8/01.

3068 **WCA-8/01**

Step	T (°C)	% ^{39}Ar	% ^{40}Ar*	^{40}Ar*/^{39}Ar	App. age
1	620	3.4	94.5	8.19 ± 1.7	244.8 ± 4.3
2	680	6.3	96.4	9.85 ± 0.7	290.5 ± 2.0
3	720	10.5	98.0	10.32 ± 0.2	303.3 ± 0.6
4	770	26.5	99.2	10.54 ± 0.1	309.3 ± 0.4
5	820	17.1	99.3	10.65 ± 0.3	312.3 ± 0.9
6	860	6.8	98.6	10.52 ± 0.5	308.8 ± 1.5
7	925	5.6	97.4	10.33 ± 0.4	303.6 ± 1.2
8	980	5.7	97.4	10.19 ± 0.9	300.0 ± 2.8
9	1060	13.7	98.4	10.66 ± 0.5	312.6 ± 1.6
10	1250	4.4	95.2	10.48 ± 1.4	307.8 ± 4.4

J = 0.017745 ± 0.4 % Total gas age: 305.3 ± 2.8 Ma
80 % plateau age: 309.3 ± 2.7 Ma

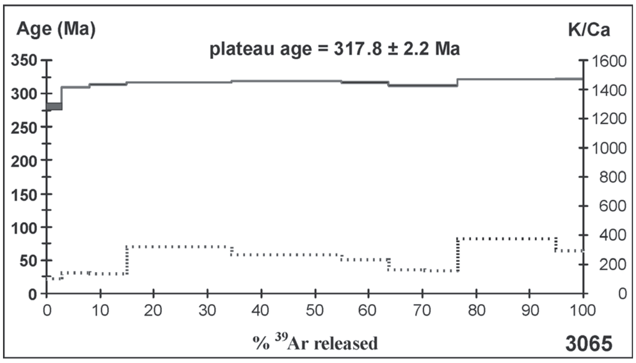

Fig. 3. $^{40}Ar/^{39}Ar$ apparent age diagram of detrital white mica from the middle part of the Nižná Boca Formation, sample WCA-7/01.

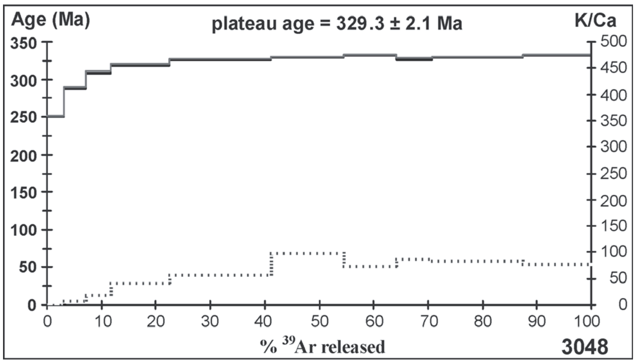

Fig. 4. $^{40}Ar/^{39}Ar$ apparent age diagram of detrital white mica from the upper part of the Nižná Boca Formation, sample WCA-4/01.

Table 2: Analytic data of detrital white mica from the middle part of the Nižná Boca Formation, sample WCA-7/01.

3065 **WCA-7/01**

Step	T (°C)	% ^{39}Ar	% $^{40}Ar^*$	$^{40}Ar^*/^{39}Ar$	App. age
1	620	2.8	94.2	9.49 ± 1.5	280.9 ± 4.2
2	680	5.2	97.2	10.56 ± 0.4	309.9 ± 1.3
3	720	7.0	98.6	10.71 ± 0.6	313.9 ± 1.9
4	770	19.5	99.2	10.81 ± 0.2	316.7 ± 0.6
5	820	20.4	99.4	10.90 ± 0.3	318.9 ± 0.9
6	860	8.7	99.5	10.80 ± 0.4	316.3 ± 1.4
7	925	6.7	99.0	10.65 ± 0.3	312.2 ± 0.9
8	980	6.1	98.8	10.63 ± 0.4	311.7 ± 1.4
9	1080	18.4	99.3	10.98 ± 0.1	321.3 ± 0.4
10	1250	5.1	99.0	11.01 ± 0.4	321.9 ± 1.3

J = 0.017745 ± 0.4 % Total gas age: 316.0 ± 2.4 Ma
91 % plateau age: 317.8 ± 2.2 Ma

Table 3: Analytic data of detrital white mica from the upper part of the Nižná Boca Formation, sample WCA-4/01.

3048 **WCA-4/01**

Step	T (°C)	% ^{39}Ar	% $^{40}Ar^*$	$^{40}Ar^*/^{39}Ar$	App. age
1	620	3.1	96.6	29.47 ± 0.4	250.8 ± 0.8
2	680	4.1	97.1	34.33 ± 0.4	289.1 ± 1.0
3	720	4.5	98.0	36.90 ± 0.7	308.9 ± 1.9
4	770	10.9	99.1	38.25 ± 0.6	319.3 ± 1.7
5	820	18.5	99.4	39.19 ± 0.1	326.5 ± 0.4
6	860	13.3	99.4	39.58 ± 0.2	329.5 ± 0.6
7	925	9.7	99.2	39.89 ± 0.3	331.8 ± 1.0
8	980	6.7	98.4	39.34 ± 0.3	327.6 ± 0.9
9	1060	16.5	98.8	39.53 ± 0.2	329.1 ± 0.5
10	1250	12.7	97.8	39.98 ± 0.2	332.5 ± 0.6

J = 0.005062 ± 0.4 % Total gas age: 323.2 ± 2.4 Ma
77 % plateau age: 329.3 ± 2.1 Ma

three samples reflects a typical feature in these clastic deposits — which has to be further tested — this indicates the evolution of the erosional source region from more local and rapidly uplifted areas to a wider region in which older portions are incorporated. In the simple case that only deeper levels in the same basement source area were eroded one should expect gradually younger ages in higher stratigraphic levels. Of course, the age distribution in the source area may have been complex considering also the age variation among the various Variscan magmatic and metamorphic crystalline rock complexes which contributed a substantial portion of the rock fragments and the detrital micas of the clastic deposits (broad spectrum of Variscan muscovite K/Ar data: Cambel et al. (1990); $^{40}Ar/^{39}Ar$ cooling ages data from Tatricum and Veporicum: Maluski et al. (1993), Dallmayer et al. (1996), Janák (1994); U-Pb zircon data: Poller et al. (2000), Poller & Todt (2000)).

The trend to older ages in higher stratigraphic levels in this tectonic unit is further corroborated by sample WCA-3/01 which is derived from the Permian Malužiná Formation, 2nd megacycle. It yielded a still older age of 342 ± 3 Ma with negligible saddle shaped rejuvenation at medium temperatures (Fig. 5, Table 4). Such features are often observed when samples have suffered some overprinting. As overprinting in sediments can be excluded, overprinting in the source region could be a possible reason for this feature.

Of course, the ages obtained cannot be interpreted as uniform ages in the source regions. As they are derived from multigrain samples a mixture from micas with somewhat different ages can be expected. Most probably the variation did not exceed the time span of the Variscan cycle.

However, the limited data from Carboniferous/Permian sediments from the Hronic tectonic unit are compatible with the formation of a tectonic graben in a recently uplifted basement and later successive widening of the erosional source area including older regions from the Variscan belt.

Muscovite K/Ar (these data published between 1957–1988 were reviewed by Cambel et al. 1990) and $^{40}Ar/^{39}Ar$ data from Tatric and Veporic basement units generally give a broad age spectrum although Hercynian cooling is completely preserved in many cases (Maluski et al. 1993; Dallmayer et al. 1996; Kráľ et al. 1997; Kohút et al. 1998; Hók et al. 2000). Very typical $^{40}Ar/^{39}Ar$ plateau ages lie between 340–320 Ma. $^{40}Ar/^{39}Ar$ muscovite data often show rather discordant spectra, which are interpreted as a result of Alpine rejuvenation.

Samples from the Carboniferous of the Northern Gemeric Unit: Four samples from this unit were investigated. The most interesting result was found from sample WCA-1/00 of the Mississippian Hrádok Formation near Ochtiná village. Here a well defined plateau age of 465 ± 2.5 Ma was measured (Fig. 6, Table 5). The low tem-

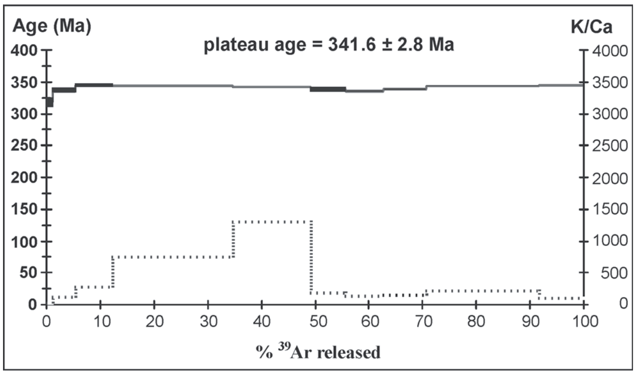

Fig. 5. $^{40}Ar/^{39}Ar$ apparent age diagram of detrital white mica from the Malužiná Formation, 2nd megacycle, sample WCA-3/01.

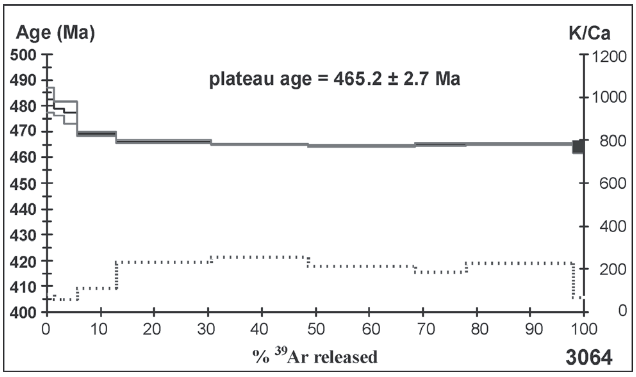

Fig. 6. $^{40}Ar/^{39}Ar$ apparent age diagram of detrital white mica from the Hrádok Formation metasandstone, sample WCA-1/00.

Table 4: Analytic data of detrital white mica from the Malužiná Formation, 2nd megacycle, sample WCA-3/01.

3067 **WCA-3/01**

Step	T (°C)	% ^{39}Ar	% $^{40}Ar^*$	$^{40}Ar^*/^{39}Ar$	App. age
1	620	1.1	95.3	10.55 ± 1.9	317.6 ± 6.2
2	680	4.4	97.4	11.28 ± 0.9	337.6 ± 3.2
3	720	6.8	99.3	11.54 ± 0.5	344.7 ± 1.7
4	770	22.4	99.5	11.49 ± 0.2	343.4 ± 0.7
5	820	14.6	99.5	11.45 ± 0.2	342.3 ± 0.8
6	860	6.4	99.1	11.30 ± 0.8	338.4 ± 2.7
7	925	7.1	98.6	11.20 ± 0.6	335.6 ± 1.9
8	980	7.9	98.4	11.32 ± 0.6	338.7 ± 1.9
9	1060	21.1	99.2	11.48 ± 0.2	343.2 ± 0.5
10	1250	8.3	98.3	11.52 ± 0.3	344.2 ± 1.1

J = 0.018250 ± 0.4 % Total gas age: 341.6 ± 2.8 Ma
100 % plateau age: 341.6 ± 2.8 Ma

Table 5: Analytic data of detrital white mica from the Hrádok Formation metasandstone, sample WCA-1/00.

3064 **G-1/00**

Step	T (°C)	% ^{39}Ar	% $^{40}Ar^*$	$^{40}Ar^*/^{39}Ar$	App. age
1	620	1.3	92.6	17.28 ± 1.2	482.4 ± 4.9
2	680	1.9	93.8	17.13 ± 0.7	478.9 ± 2.9
3	720	2.3	96.0	17.08 ± 1.0	477.5 ± 4.2
4	770	7.4	98.1	16.73 ± 0.2	469.0 ± 0.8
5	820	17.7	99.5	16.62 ± 0.1	466.2 ± 0.5
6	860	18.1	99.7	16.57 ± 0.1	465.0 ± 0.3
7	925	19.8	99.6	16.55 ± 0.1	464.6 ± 0.3
8	980	9.6	99.5	16.57 ± 0.1	465.0 ± 0.6
9	1060	20.0	99.7	16.58 ± 0.1	465.2 ± 0.4
10	1250	2.0	98.6	16.53 ± 0.6	464.0 ± 2.3

J = 0.017745 ± 0.4 % Total gas age: 466.2 ± 2.7 Ma
87 % plateau age: 465.2 ± 2.4 Ma

perature steps of this diagram exhibit some higher ages, which is unusual for undisturbed spectra of detrital muscovites. A ^{39}Ar recoil effect (^{39}Ar loss from altered mineral lattice during irradiation) resulting from strongly weathered rims of the detrital grains seems to be a possible explanation for this feature.

We think that this well defined concordant age spectrum reflects the cooling in the source region and not mixing of widely differing ages. In the Alps such Early Paleozoic ages have been often measured with Rb/Sr whole rock dating on orthogneisses, but are only seldom preserved in the minerals. During sedimentation of the Hrádok Formation such a crustal element obviously delivered the dominating clastic contribution. The question arises if such ages are typical of the Hrádok Formation or restricted to local occurrences therein.

Metasandstone sample WCA-3/00 is also derived from the Hrádok Formation. Here a metamorphic overprint in the matrix is visible. Fine-grained phengite from the matrix could be separated from this location and yielded a distinct staircase pattern from 87 Ma at the rim to 142 Ma in the core (Fig. 7, Table 6). Alpine metamorphic

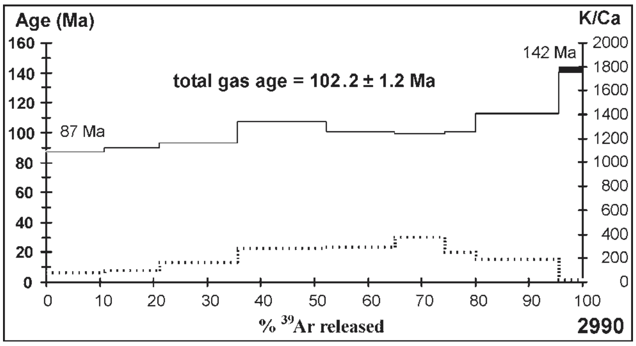

Fig. 7. $^{40}Ar/^{39}Ar$ apparent age diagram of newly-formed fine-grained white mica from the Hrádok Formation metasandstone, sample WCA-3/00.

Table 6: Analytic data of newly-formed white mica from the Hrádok Formation metasandstone, sample WCA-3/00.

2990 **G-3/00**

Step	T (°C)	% ^{39}Ar (rel.)	% $^{40}Ar^*$	$^{40}Ar^*/^{39}Ar$	App. age
1	680	10.7	93.2	2.70 ± 0.6	87.4 ± 0.5
2	720	10.3	95.6	2.79 ± 0.6	90.4 ± 0.5
3	770	14.6	96.3	2.90 ± 0.5	93.8 ± 0.5
4	820	16.7	97.8	3.34 ± 0.5	107.6 ± 0.5
5	860	12.6	96.5	3.09 ± 0.4	101.2 ± 0.5
6	925	9.3	95.1	3.09 ± 0.4	99.9 ± 0.4
7	980	5.8	91.8	3.13 ± 0.6	100.9 ± 0.6
8	1060	15.4	97.2	3.52 ± 0.3	113.3 ± 0.4
9	1250	4.5	89.0	4.46 ± 1.2	142.2 ± 1.7

J = 0.018400 ± 0.4 % Total gas age: 102.2 ± 1.2 Ma
80 % plateau age: 97.8 ± 1.2 Ma

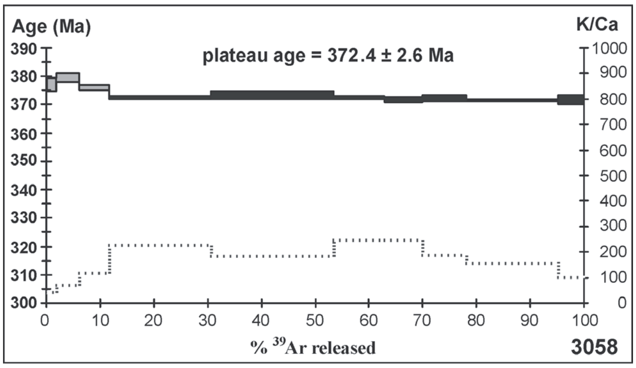

Fig. 8. $^{40}Ar/^{39}Ar$ apparent age diagram of gneiss pebble muscovite from the Rudňany Formation conglomerate, sample WCA-9/01.

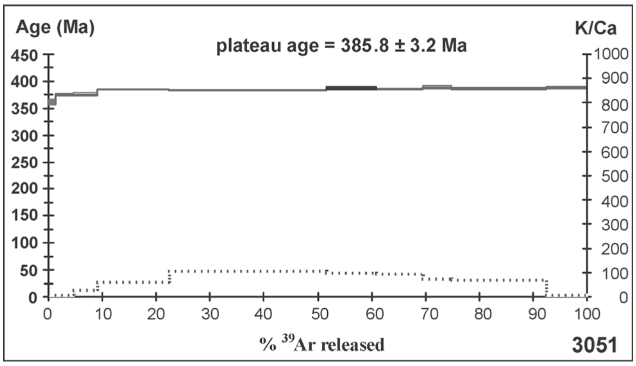

Fig. 9. $^{40}Ar/^{39}Ar$ apparent age diagram of detrital white mica from the Rudňany Formation sandstone, sample WCA-9/98.

Table 7: Analytic data of gneiss pebble muscovite from the Rudňany Formation conglomerate, sample WCA-9/01.

3058 **WCA-9/01**

Step	T (°C)	% ^{39}Ar	% ^{40}Ar*	^{40}Ar*/^{39}Ar	App. age
1	620	1.9	94.4	13.10 ± 0.7	377.0 ± 2.3
2	680	4.2	97.2	13.19 ± 0.4	379.4 ± 1.5
3	720	5.5	98.1	13.06 ± 0.3	376.1 ± 0.9
4	770	19.0	98.7	12.92 ± 0.2	372.4 ± 0.7
5	820	22.9	99.4	12.95 ± 0.4	373.3 ± 1.4
6	860	9.3	99.5	12.93 ± 0.2	372.6 ± 0.6
7	925	7.1	98.9	12.90 ± 0.3	371.8 ± 1.0
8	980	8.2	99.0	12.92 ± 0.3	372.4 ± 1.0
9	1060	17.2	99.3	12.89 ± 0.1	371.7 ± 0.4
10	1250	4.7	98.9	12.89 ± 0.5	371.7 ± 1.6

J = 0.017745 ± 0.4 % Total gas age: 373.0 ± 2.7 Ma
88 % plateau age: 372.4 ± 2.6 Ma

Table 8: Analytic data of detrital white mica from the Rudňany Formation sandstone, sample WCA-9/98.

3051 **G-9/98**

Step	T (°C)	% ^{39}Ar	% ^{40}Ar*	^{40}Ar*/^{39}Ar	App. age
1	620	1.3	93.4	43.86 ± 1.6	361.7 ± 5.4
2	680	3.2	97.8	45.71 ± 0.5	375.5 ± 1.5
3	720	4.5	98.5	45.78 ± 0.9	376.0 ± 3.0
4	770	13.4	99.1	47.01 ± 0.1	385.1 ± 0.5
5	820	29.2	99.7	46.83 ± 0.4	383.8 ± 1.3
6	860	9.2	99.1	47.33 ± 0.8	387.5 ± 2.9
7	925	8.7	99.7	47.09 ± 0.3	385.7 ± 0.9
8	980	5.3	99.2	47.59 ± 0.9	389.3 ± 2.4
9	1060	17.6	99.6	47.22 ± 0.5	386.6 ± 1.6
10	1250	7.6	98.4	47.53 ± 0.4	388.9 ± 1.2

J = 0.005062 ± 0.4 % Total gas age: 384.7 ± 3.4 Ma
90 % plateau age: 385.8 ± 3.2 Ma

evolution, in the Northern Gemeric/Veporic contact zone, was related to the growth of the Western Carpathian orogenic wedge mainly during the Cretaceous time. It was a consequence of crustal thickening and post-burial thermal relaxation of geotherms during the initial stage of exhumation, connected with local intrusions of the Cretaceous granitoids (Vozárová 1990; Janák et al. 2001).

One can expect that small, still older age domains exist in the tiny phengites. Because stepwise heating of multigrain samples cannot produce gas from a single domain, it is always a mixture from different domains. We therefore interpret this result as a typical formation age over a prolonged time of crystallization with some strongly rejuvenated clastic remnants.

From the Westphalian Rudňany Formation we investigated two samples. Sample WCA-9/01 (quarry near Závadka village) is a muscovite from a large orthogneiss pebble, it yields an exceptionally well defined plateau age of 372 ± 3 Ma, reflecting the age of cooling of the orthogneiss in the source area (Fig. 8, Table 7).

A slightly older age (Fig. 9, Table 8) 386 ± 3 Ma was measured on detrital micas from sandstones near Rudňany village (sample WCA-9/98). Such Late Devonian ages are obviously typical in the Westphalian clastic sediments. They indicate a time difference between cooling and sedimentation of approximately 50–60 Ma.

Discussion and interpretation

The fundamental fact that the substantial part of the late Variscan crust was remobilized and shortened during the Alpine compression events, leads to the greatest difficulty in the reconstruction of the Variscan Orogeny in the Western Carpathians. The Western Carpathian Upper Paleozoic sedimentary basins originated in consequence of Variscan continent/continent collision of two microplates. Relics of these colliding microplates are preserved as fragments of crystalline basement rocks within the main crustal-scale units of the Alpine Western Carpathians internides (the Tatricum, Northern Veporicum, Southern Veporicum, Hronicum, Zemplinicum and Northern Gemericum; Fig. 1). The three types of Variscan crystalline fragments in the Alpine Western Carpathians were distinguished as: the Central Western Carpathian Crystalline Zone (CWCZ), the Northern Gemeric Zone (NGZ) and Inner Western Carpathian Zone (IWCZ). The main differences between these zones are in their Variscan geodynamic evolution as well as in the chronological and spatial evolution of Upper Paleozoic basins (Vozárová 1998). These crustal fragments correspond to two colliding microplates, one represented by medium- to high-graded crystalline complexes and magmatites of the CWCZ (crystalline rock complexes and derived Upper Paleozoic post-orogenic sequence preserved in the Tatricum, Veporicum, Zemplinicum and Hronicum) and the second represented by the IWCZ low-grade crystalline (Lower Paleozoic complexes of the Southern Gemeric Unit with its Permian cover). The CWCZ were separated from the IWCZ by the NGZ (preserved in the Northern Gemeric Unit), with the Mississippian deep water turbidites (Noetsch–Veitsch–Ochtiná zone after Flügel 1990; North Gemeric–Veitsch zone after Neubauer & Vozárová 1990).

The Variscan convergence led to closing and suturing of the Rakovec oceanic domain, easternmost remnants of the Rheic Ocean. The main collision stage occurred during the Late Devonian–Mississippian. This was associated with the origin of the intrasuture deep to shallow water embayment during the Mississippian. Representative are sediments of the Ochtiná Group, primarily the turbidites of the Hrádok Formation. The relatively old 465 Ma $^{40}Ar/^{39}Ar$ age of detrital mica (Fig. 6, Table 5), from the metasandstones of the Hrádok Formation, reflects the existence of crustal fragments with the imprint of intra-Ordovician events in the supposed collision suture zone. (The term "Caledonian" is used for magmatic-metamorphic processes as a certain time interval.) Similar Caledonian age data are preserved within the Central and Southern Alps, in areas of a lower-grade Alpine overprint. Orthogneisses and paragneisses from different complexes were dated at about 440–470 Ma, based on Rb/Sr whole-rock analyses and U-Pb zircon data (Grauert 1966; Köppel et al. 1980 and others). Eclogite facies metamorphism at ca. 470 Ma is indicated by Sm-Nd analyses on whole rock and garnet in the Gotthard Massif (Gebauer et al. 1988; Gebauer 1990). There is a clear proof for compressional events starting with the formation of eclogites, probably in a subduction zone setting, at ca. 470 Ma (Gebauer et al. 1988; Gebauer 1990).

Cambrian-Ordovician magmatic and metamorphic activity is also documented by 514±24 Ma U-Pb zircon data (Putiš et al. 2001) and 468±24 Ma EMPA monazite ages (Janák et al. 2002) from the Tatricum and Northern Veporicum metamorphic complexes in the Western Carpathians.

The $^{40}Ar/^{39}Ar$ age of detrital mica from the Mississippian of the Northern Gemeric Unit is the first evidence of Ordovician crustal fragments within the supposed Variscan collision suture in the Western Carpathians. The sedimentary filling of this intrasutural remnant basin was the only possibility for the preservation of such old relics, because Variscan convergence completely overprinted and reworked these Ordovician crustal fragments. The climax of the Variscan collision is dated by the $^{40}Ar/^{39}Ar$ ages of detrital mica as well as orthogneiss pebble muscovite from the Westphalian Rudňany Formation, which gave cooling ages of 385.8±3.2 Ma and 372±3 Ma, respectively (Fig. 8, Table 7).

The dynamics of convergence were modified by the dextral translation between Europe and Africa (Ziegler 1988; 1990) and the formation of the Pennsylvanian continental basins in the CWCZ. The $^{40}Ar/^{39}Ar$ ages from detrital mica of the Pennsylvanian and Permian sediments of the Hronicum document clearly that increasingly older pieces of the continental crust were involved in erosion due to wrench faulting and rifting behind the Variscan suture zone (Figs. 2, 3, 4, 5; Tables 1, 2, 3, 4). The relatively broad time span in $^{40}Ar/^{39}Ar$ ages of detrital micas is related to a temporal progression of the Hronicum rift system. The tectonic development of this terrestrial rift, interpreted from the distribution of lithofacies, the composition of detrital material and the character of synsedimentary volcanism, shows that the upper-crustal extension was spatially variable. According to a numerical model of Buck (1991) the mode of extension is controlled by crustal thickness and thermal conditions at the time of rifting. In a *core-complex mode* the upper-crustal extension is concentrated over a narrow region, while the lower crust is thinned over a broad area. This occurs when the crust, due to crustal thickening in the compressional stage, is hot and thick. The younger $^{40}Ar/^{39}Ar$ ages of detrital mica from the Nižná Boca Formation, could reflect this initial stage of rifting. When the lower crust flows slowly, then the mode of extension depends on the strength of the lithosphere: a) *wide-rift mode* — hot and weak lithospere; b) *narrow-rift mode* — cold and strong lithosphere (Buck 1991).

As indicated by the chemistry of synsedimentary volcanism, and differences between the 1st and 2nd eruption phase (Vozár 1997), the Upper Paleozoic Hronic sedimentary basin may be an example of a region that has passed through all three stages. Dominant silicic volcanism during sedimentation of the Nižná Boca Formation may have accompanied core-complex mode extension and may have resulted from decompression melting. In contrast, dominant andesite-basalt tholeiites as synsedimentary volcanics during sedimentation of the Malužiná Formation (Vozár 1997; Dostal et al. 2003) indicate rather colder and stronger lithosphere, with mantle-derived magma ascent along rift-related faults. The sedimentary architecture was controlled by episodicity of footwall-generated sediment discharge into depocenters leading to a heterogeneity of provenance. The $^{40}Ar/^{39}Ar$ ages of detrital micas from Hronicum sediments support this model.

Conclusions

Dating of detrital white mica taken from the Carboniferous-Permian sediments of the Western Carpathians provided important results for the determination of source areas. Two groups of studied samples, from the Carboniferous formations of the Northern Gemeric Unit and from the Pennsylvanian-Permian sequence of the Hronic Unit yielded the following ages:

1 — *Northern Gemericum:* A multi-grain sample from the Pennsylvanian Hrádok Formation yielded a 465±2.5 Ma cooling age of the source area. This age proves the existence of Ordovician crustal pieces in the initial stage of Variscan collision suture. Newly-formed fine-grained muscovite gave a distinct staircase pattern from 87 Ma at the rim to 142 Ma in the core. It reflects a composite Alpine overprint of these metasediments.

Multi-grain analyses of detrital mica and orthogneiss pebble muscovite from the Westphalian Rudňany Formation yielded 385±3 Ma and 372±2.5, reflecting a uniform Variscan source.

2 — *Hronicum:* Rift-related sediments of the Hronic Unit showed a trend of increasingly older detrital mica upward. Cooling ages in the source area may reflect the development of Hronicum terrestrial rift and the heterogeneity of the source area, with gradual rifting and cooling of the lithosphere.

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